# VTOL Analysis for Emergency Response Applications (VAERA) - Identifying Technology Gaps for Wildfire Relief Rotorcraft Missions

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## ABSTRACT

The mission of VAERA (VTOL Analysis for Emergency Response Applications) is to enable the design, development, and analysis of emergency response rotorcraft for different disaster scenarios. The project's current focus is on improving crewed and uncrewed rotorcraft for wildfire relief efforts. This paper presents background information on the current state of the art for wildfire-fighting crewed and uncrewed rotorcraft, current wildfire operations, handling and flying qualities considerations of similar vehicles, and the limitations of uncrewed sub-1000 lb commercial off the shelf (COTS) rotorcraft that could be (and sometimes are) used for different wildfire missions. Technology gaps that are currently limiting rotorcraft firefighting capabilities are identified using the background information, and a plan of how to address each of the identified technology gaps is presented. In this paper, the key technology gaps identified for rotorcraft in the wildfire environment include: poor performance and handling/flying qualities, inadequate or nonexistent categorization of handling qualities, unvalidated flight dynamics turbulence modeling approaches, and inadequate subsystems for wildfire missions. While numerous concerns for rotorcraft operating in the wildfire environment exist, this paper focuses on those issues that are either not being addressed by others, or that require more attention. The goals of this paper are to both educate the public on critical technology gaps for wildfire-fighting rotorcraft that have not gained significant traction in the public domain, and to explain the work required to address those technology gaps.

## INTRODUCTION

Wildfires pose a notable risk to both human lives and property, a risk which is becoming a larger concern as the past several decades have seen a significant rise in wildfire events. Data published by the National Interagency Fire Center (NIFC) demonstrate an alarming and persistent upward trend of both the annual financial cost and acreage burned associated with wildfires over the past decade [1]. Recorded data, summarized in Figure 1, shows that between 1985 and 2022, the 5-year average for annual cost related to wildfire suppression increased over 4-fold, while acreage burned increased over 2.5-fold. It is important to note that the presented annual costs are only for wildfire suppression. While difficult to precisely define, the true annual cost of wildfires is likely significantly higher. In 2018, the total cost of wildfires in California was estimated to be over 148 billion dollars, with 22% of that cost deriving from healthcare costs alone [2]. When further classifying wildfires by size, records show that between 1984 and 2015, the number of "large" wildfires, as classified by the Center for Climate and Energy Solutions, has nearly doubled. In California, five of the six largest fires on record occurred in 2020 [3].

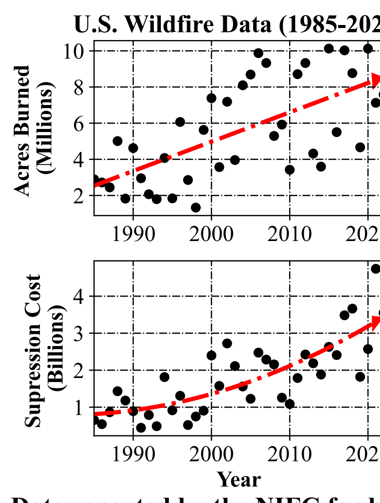


**Figure 1. Data reported by the NIFC for both annual acres burned and federal wildfire suppression costs ranging from 1985-2022. Results include private, state, and federal lands within the United States for each fiscal year [1].**

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Given that the upward trend in wildfires is closely tied to climate change [4], the recent increase in wildfires is likely not a temporary event but rather is the "new normal" [5].

The significant and persistent rise in wildfires has prompted firefighting organizations to explore new technologies, techniques, and procedures to help mitigate this growing threat to life and property. While firefighters have been utilizing commercial off the shelf (COTS) vehicles that offer some capabilities to support wildfire missions (i.e. water drops and surveillance), more advanced vehicles – specifically designed for wildfire missions – may provide game changing improvements in terms of reducing fire damage, saving lives, and increasing situational awareness and safety for the firefighters on the front lines. U.S. Government agencies including the Department of Agriculture (USDA), Forest Service (USFS), and NASA are very interested in developing such capabilities via unmanned aerial vehicles (UAVs) and drone technology.

The main objective of VAERA (VTOL Analysis for Emergency Response Applications) is to enable the design, development, and analysis of emergency response rotorcraft for different disaster scenarios. The project utilizes state-of-the-art NASA tools and processes to identify and fill technology gaps for emergency response scenarios. Currently, the work is focused on wildfire relief efforts; however, future work will involve analysis, design, and development of a variety of emergency and disaster relief vehicles and technologies. This paper presents a compilation of the research, builds upon previous emergency aircraft studies in the Aeromechanics Office at NASA Ames Research Center, and leverages lessons learned from recent NASA research in Urban Air Mobility (UAM) across NASA centers. Additionally, this paper discusses the current state of the art for wildfire-fighting rotorcraft, identifies technology gaps that are currently limiting rotorcraft firefighting capabilities, and offers methods and approaches by which those technology gaps might be addressed.

## HISTORY OF PUBLIC GOOD MISSIONS AT NASA AMES RESEARCH CENTER

Through the Advanced Air Mobility (AAM) mission, NASA is currently working toward improving the future of flight through a number of projects that will advance the scope and efficiency of aircraft performing public good missions. The vision of AAM is to establish a future in which aviation is more accessible, affordable, safe, and sustainable [6]. There are several practical applications for AAM, such as Urban Air Mobility (UAM), small Unmanned Aircraft Systems (sUAS), and Regional Air Mobility (RAM). These applications have varying missions and overarching goals to improve aviation infrastructure, passenger transport, airspace management, package delivery, aerial surveying and photography, and emergency services that could serve the public good. While all of these goals are important, in this section, the discussion will be limited to AAM topics directly related to the development of airspace management and vehicle design and analysis for emergency wildfire response.

NASA Ames Research Center has a vested interest in exploring solutions for emergency response to wildfires due to the increasing severity of fire seasons, particularly in the Western United States. Scalable Traffic Management for Emergency Response Operations (STEReO) is a NASA Ames project that partners with the United States Forest Service (USFS) and the California Department of Forestry and Fire Protection (CAL FIRE) to develop tools that use real-time, accurate wildfire data and communicate the data effectively to emergency responders and subject matter experts (SMEs) [7]. These tools focus primarily on four areas of interest: autonomy, communication, human factors, and the UAS Traffic Management (UTM) system [8]. STEReO's goal is ultimately to provide tools that enhance the operational capability of aircraft in disaster scenarios by enabling faster response to emergencies, addressing technology gaps in current UTM systems, advancing autonomous technologies, and fostering the growth of UTM technologies [9].

The Advanced Capabilities for Emergency Response Operations (ACERO) project at NASA Ames is similarly exploring ways to modernize and improve technologies for wildfire operations in collaboration with existing partners such as the USFS, CAL FIRE, the Federal Aviation Administration (FAA), and the Japan Aerospace Exploration Agency (JAXA). The development of technologies that can identify, monitor, and suppress wildfires will enable the ACERO project to enhance the safety of flying in dangerous airspace. These technologies will improve surveillance, navigation, communication, and mission support capabilities in disaster zones [10].

The ACERO and STEReO projects primarily focus on air traffic management, improvements to airspace control technologies, and the implementation and collaboration of wildfire relief vehicles within the airspace. These efforts support the operational side of technology development, with an emphasis on communication for wildfire relief and response. The work of VAERA, discussed in later sections of this paper, focuses on vehicle-specific technology development and analysis for rotorcraft in emergency and disaster scenarios, specifically with a current focus on wildfires.

Over the years, novel vehicle concepts have been proposed to meet the need for robust, efficient, and sustainable vehicle configurations for various emergency response situations. In a 2010 study by Young, robotic rescue devices were proposed for various potential disaster relief and emergency response (DRER) missions, including search and rescue operations, aerial surveys, surface interaction, equipment deliveries, aerial transport, and security missions [11]. A separate study, the Smart Precise Rotorcraft InTerconnected Emergency Services (SPRITES) system, was proposed by Young in 2017 and provides an analysis of notional vehicle and network concepts capable of achieving a number of DRER missions [12]. These novel concepts helped build the foundation for potential mission criteria of emergency response rotorcraft. Another case study by DeBusk demonstrated the application of a civil unmanned aerial system to obtain advanced warning and damage assessments for tornados and severe thunderstorms [13]. The early work of the VAERA project is inspired by and leverages the unique capabilities proposed by the NASA projects mentioned above. Collaborative relationships across divisions at NASA, other government agencies, and industry demonstrated by STEReO, ACERO, and SPRITES provide the project architecture to enhance vehicle concepts in future studies.

## CURRENT WILDFIRE RESPONSE

Wildfire response is mainly performed with humans on the front line. When a fire is spotted, firefighter crews are dispatched to the area where they can perform either a direct or indirect attack. A direct attack involves directly treating burning fuel, while an indirect attack attempts to contain the fire from a safe distance. Wildfires are mainly controlled through indirect attacks such as fire lines and controlled burns, with both tasks aiming to remove fuel from the fire path. Fire line construction involves large teams, often working in remote areas, removing trees and brush, and turning over a layer of soil. Controlled burns involve a small team using drip torches to ignite small areas of fuel. Crew lives are at constant risk of hazards such as falling trees, smoke, visibility issues, and fire-induced weather conditions [14].

In concert with the indispensable human element to firefighting, aircraft play an important air support role in wildfire operations. Both fixed-wing aircraft and rotorcraft can perform similar tasks, with selection often based on factors such as location of operations, required speed, and availability of aircrew and aircraft. Both types of vehicles can be used to perform water or retardant drops along the fire line. For these operations, water can be collected from nearby sources with either a bucket or snorkel system, depending on the water source selected and location of the fire. Both types of vehicles are also used for reconnaissance efforts. Additionally, air support is often used to move crews to the command center or work locations. Certain crews, known as smokejumpers, will parachute from aircraft into a remote fire location to construct fire lines [15].

The ability to hover and take off vertically gives helicopters major advantages in moving crews and supplies. Helicopters can land at improvised landing sites to drop off crews, which is essential if the fire is not located near an established airport or landing area. Helicopters are also commonly used for supply drops to fire camps. Furthermore, helicopters are occasionally used for personnel rescue missions, if conditions allow [16]. These operations often mean a crew is utilizing several air support craft for their operations. For example, CAL FIRE uses, at minimum, one air attack vehicle, two air tankers, and one to two helicopters (often a Bell UH-1H or Sikorsky Firehawk) [17].

Air support faces several risks and limitations. One of the biggest threats to air support is visibility, with smoke concealing dangerous obstacles, terrain, and even other air support craft. Helicopters often fly lower than fixed-wing aircraft and risk running into power lines and towers. There is also a constant risk of privately operated drones interfering with operations, despite the FAA issuing Temporary Flight Restrictions near fires [16]. This risk means air support operations are typically limited to daytime only, and pilots are instructed to avoid flying near smoke plumes unless absolutely necessary [18]. There are also limitations on pilot flight time, with shifts restricted to seven hours [17]. Given these limitations for crewed aircraft, an uncrewed vehicle – which can fly at all hours (not just daytime), in the smoke, and into dangerous areas where crewed vehicles are prohibited – offers significant advantages and enables missions that are not safe for crewed aircraft.

## TECHNOLOGY GAPS

This section will identify and discuss some of the technology gaps restricting rotorcraft from performing and executing challenging missions in wildfire environments.

### Wildfire Environment Modeling and Simulation

Whether it be from ship-wake interactions [19], rotor-rotor interference [20], or operating in an urban setting [21], turbulent environments have remained a significant challenge to the safe operation of rotorcraft across a broad range of military and civilian applications. For several notable turbulent operating environments of rotorcraft, numerous disturbance rejection-based control architectures [22] and vehicle designs [23] have been explored to help alleviate pilot workload and increase overall flight safety. Yet, as electric Vertical Take-Off and Landing (eVTOL) rotorcraft continue to expand the envelope of operations, new environments with distinct levels of turbulence and underlying flow field complexities will be encountered. For the field of urban air mobility, examples that have received significant focus in recent years include urban environments and flying multiple rotorcraft in close proximity [24]. As eVTOL aircraft are further leveraged to assist in emergency response missions, notably fire suppression missions [25], historical experience in the rotorcraft field has shown that both an enhanced understanding of the environmental turbulent characteristics, and an ability to model such characteristics, will be required to safely operate such vehicles. Fortunately for vehicle designers and operators, a rich history of research exists in the literature focused on the interactions between atmospheric turbulence and wildfires, with articles dating back well over 100 years [26] [27]. Additionally, prior experience in the broader rotorcraft field has provided several notable approaches toward modeling vehicles operating in turbulent environments. This section of the paper summarizes both the key underlying characteristics of the wildfire-driven turbulent environment and potential approaches toward modeling such environments. It is noted that the proceeding summary is not intended to be a comprehensive description of the wildfire-driven atmospheric flow field, but rather to emphasize the complexities of the fire-driven turbulence as well as the limitations of current numerical modeling approaches. For a more comprehensive review of atmospheric and wildfire-driven turbulence, readers are encouraged to read one of the many review papers on the topic [28] [29] [30] [31].

Inherent to the wildfire environment are the numerous large-scale eddies present in the flow field [32]. Driven by an initial vertical shear layer generated by fire-induced buoyancy, referred to as Rayleigh-Bernard convection, velocity and density driven instabilities lead to a distinct breakdown of the flow and subsequent generation of large coherent features. Additionally, both experimental and numerical investigations have demonstrated that wildfire driven flow fields not only generate their own turbulence but also reorientate and amplify eddies already present in the atmosphere [33]. An example of the ambient atmospheric vortices amplifying as they pass through the wildfire is depicted in Figure 2. Once the turbulence is generated, there exists a plethora of coherent features which may appear in a wildfire-generated flow.

One predominant example of a wildfire-generated flow feature, which has seen significant attention in the literature, is the vertical fire whirl [34]. Fire whirls, sometimes referred to as fire devils, can form due to a variety of underlying mechanisms including reorientation of atmospheric eddies, cross winds interacting with the fire front, local terrain, etc. Yet, regardless of how these initial whirls form, they can eventually shed from the wildfire and be convected downstream leading to a significant danger for aircraft.

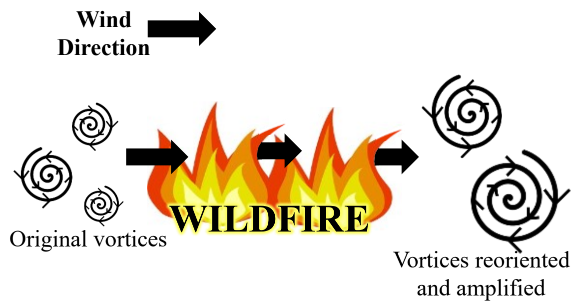


**Figure 2. Graphic demonstrating the amplification of atmospheric vortices as they transverse through the wildfire.**

The magnitude and size of the fire whirls can also vary drastically depending on a variety of parameters. Multiple sources report diameters for fire whirls between 1 m and 3 km, wind speeds ranging between 10 to 50 m/s, and a possible vortex height of 5 km [35] [36]. Yet, the literature reflects several attempts to identify a generalized scaling law for these vertical fire whirls. In work completed by Kuwana et. al. [37], a Buckingham Pi dimensional analysis was utilized to identify the interdependency between fire whirl height and circulation. Experimental data for fire whirls of various sizes showed a close comparison between experiment and the identified scaling law. While fire whirls are flow features of particular interest for flying rotorcraft, they are not the only features present in the flow. For example, in listing the predominate vortical features of interest, Forthofer and Goodrick listed seven common vortical features formed in wildfires [35]. Compounding the complexities of the environment is that, due to buoyancy effects, velocity magnitudes of upward drafts generated by these vortices can often increase with altitude, posing further danger to aircraft operators [38]. In measurements taken by Rodriguez et. al., airborne radar measurements demonstrated that gust amplitudes not only persisted but continued to increase in magnitude up to altitudes of 5 km [38].

An additional concern for both the safe operation and maintenance of rotorcraft is the high temperatures a vehicle may experience while operating near wildfires.

These high temperatures may lead to both degraded propulsive performance and expose the aircraft to fatigue cycling over the course of multiple missions. Previous experiments have identified that, even for a relatively small fire, persistent temperatures exceeding 120 °F (49 °C) can be found up to 100 ft above the fire [39]. Further studies have since demonstrated that coherent features in the flow field can drive isolated packets of high-temperature air exceeding 250 °F (121 °C) to similar altitudes [40].

In general, the wildfire flow field can vary significantly depending on a broad range of parameters. A non-exhaustive list of these parameters includes fuel source, terrain, atmospheric conditions, fire size, and location with respect to fire front. Experimental measurements have shown that velocity perturbation magnitudes experience a significant variation across the frequency spectra depending on whether measurements are taken before, during, or after passages of the fire front [41]. In this context, the term fire front refers to the location of the active fire as the transient fire transverses across a specified distance. Additionally, as noted by Crosby [42], terrain roughness can further generate turbulent eddies in the flow field, helping to promote fire spread and thus ultimately increasing overall fire-generated turbulence.

While the magnitude of such vortices varies greatly, their formation ultimately provides a significant danger to the operation of vehicles in the wildfire environment. Despite nearly a century of research into characterizing fire-generated atmospheric turbulence, over a quarter of all firefighter fatalities between 2000 and 2013 were aviation-related fatalities [43]. While it remains difficult to identify which aspect of the wildfire environment directly caused each incident, it is clear that a reliable and accurate approach to simulating rotorcraft operating in such an environment is needed. Fortunately, through decades of maturation of rotorcraft-based turbulence models, several potential modeling approaches have been derived.

Of the many possible approaches available to flight dynamics engineers, one commonly used approach is that of the isotropic stochastic turbulence models. While several stochastic turbulence models have been derived, these models all aim to numerically model a homogeneous field of isotropic turbulence. To generate these stochastic models, researchers generally attempt to derive a function defining the power spectral density (PSD) of the predicted turbulence fluctuations. This function for the PSD is typically derived by leveraging extensive measurements of atmospheric turbulence under a variety of ambient conditions and geographic locations [44]. Through these extensive measurements, engineers are then able to relate parameters of interest, such as altitude, ambient wind speed, regional atmospheric conditions, and severity of weather, to the expected velocity perturbations of the flow field.

To generate the desired turbulent perturbations, one common modeling approach is to estimate a transfer function from the identified PSD function, such as the Dryden model for example [45]. This transfer function can then be excited with a Gaussian white noise signal to produce a stochastic turbulence signal. The advantage of the stochastic modeling approach is its ability to efficiently generate a turbulence signal that matches the PSD signature of the expected atmospheric turbulence. For this reason, the utilization of such modeling approaches can be found extensively in the literature [46] [47]. Yet, when considering the case of modeling the wildfire environment, there is a crucial modeling limitation that may greatly limit the applicability of such modeling approaches.

To limit computational expense, an essential modeling assumption is that the produced turbulent signal is both isotropic and stationary in time. These assumptions allow for the efficient modeling of a given turbulent field's velocity perturbations' PSDs, but it ultimately limits such modeling approaches from predicting anisotropic and non-stationary events, such as gusts or coherent vortical flow features. As previously identified in this section, the wildfire generated flow field often contains several, large-scale, highly energetic vortical features. For the accurate numerical emulation of such an environment, these vortical flow features must be sufficiently represented in a turbulence model if vehicles dynamics are to be accurately predicted.

For turbulence modeling of environments where large, anisotropic flow features are required to be modeled, researchers often rely on computationally expensive computational fluid dynamics (CFD) solutions. Given the significant advancements in the field of high-fidelity CFD over the past several decades, modern large eddy simulation (LES) based solutions are often capable of achieving a close comparison with experimental measurements, even for wildfire-based cases [40]. Yet, this high degree of accuracy comes at an enormous computational expense, often requiring several days, if not weeks, to compute.

Given the large computational expense required to numerically model a high-fidelity representation of the turbulent flow field, modeling the full flight dynamics of the rotorcraft directly in the CFD solution becomes infeasible. As such, for applications where anisotropic effects are necessary to model, one approach taken by researchers is to decouple the interaction between the rotorcraft and the wake. In this approach, a CFD simulation is completed a priori, wherein time-dependent solutions for the flow field are saved. To simulate the interaction of the turbulent field with the rotorcraft, this CFD computed turbulent field can then be coupled with a blade element representation of a rotor. In this approach, prior compute time dependent velocity perturbations are linearly interpolated to each element of the rotor, from which hub loads are then transferred to the rotorcraft. Thus, this approach allows a feasible and computationally efficient approach to emulating vehicle response to a given turbulent environment. Examples for applications of similar modeling approaches can be found for ship-wake interactions [48] and wind turbines [49].

However, this modeling approach is not without its own limitations. One significant limitation is the one-way coupling between the CFD computed field and the rotor. While the flow field is interpolated onto the rotor, there is no ability for the rotor to alter or influence the flow field. This limitation may lead to significant deviations between simulations and flight test data if relative speed between a given vortex and rotor becomes too low. As such, further work is required to identify how well suited such modeling approaches are for the wildfire environment.

**Handling and Flying Qualities**

Aircraft need to be vigorously analyzed to provide favorable stability and control characteristics which are commonly referred to as flying qualities. While flying qualities describe the capabilities of the system itself, handling qualities describe the operating characteristics of an aircraft with a human pilot in the loop. These are also important to consider because human operators introduce additional delays, dynamics, and limitations into the control system. Understanding how these factors interact and the amount of compensatory effort a pilot must exercise in order to operate a vehicle is crucial to ensuring flight safety [50]. Vehicles that require high workloads for control may lead to task saturation and fatigue, which diminishes a pilot's situational awareness, reduces the length of time they can fly, and hinders their ability to manage system failures (among other contingencies) [51].

With the growing number of conceptual aircraft designs, particularly in the domain of AAM, the FAA and its European counterpart, the European Union Aviation Safety Agency (EASA), have been overwhelmed with the task of certifying vehicles which do not neatly fall within the heritage categories of fixed-wing and helicopter designs. To address this, both agencies have been considering the use of handling quality assessments to show compliance with safety regulations [51] [52].

Handling qualities (and flying qualities by association) play an important role in nominal aircraft operations. With emergency response scenarios, the factors affecting handling qualities are amplified tremendously. Poor weather conditions, degraded visual environments, and the added pressures on pilots to work expeditiously when lives could be at risk, are just a few of the additional aspects which further warrant these assessments. Unfortunately, handling quality assessments for emergency response vehicles are scarce. This may be due to the fact that aerial vehicles are not traditionally designed for emergency-response-specific scenarios. In a July 2023 article, Button explains that, for firefighting applications, purpose-built vehicles are typically avoided due to the expensive certification process and that government surplus vehicles can be obtained and modified for a fraction of the cost [53].

The following include several examples of issues aircraft have flying in emergency and disaster environments. One study by Klyde, et al. [54] looked at the handling qualities of a Boeing 747 and DC-10 for an aerial retardant delivery mission, but other studies specifically dedicated to handling-qualities were not forthcoming. In terms of rotorcraft specifically, two studies were found involving the use of helicopters for fighting fires in high rise buildings. Saito et al. included a flight test where the pilot flew parallel to a building and reported difficulties maintaining a constant 20-meter distance (varied 16-30 meters) and a constant heading [55]. Zanenga, Leonello, and Bottasso studied how the coupled dynamics of a water cannon and human reaction delays affected ADS-33 performance of a Bell 412 [56]. This study used a mathematical human pilot model to estimate Level 2 handling qualities for the Agusta-Bell AB412 and noted degradation to Level 3 yaw performance when the canon was mounted with an azimuth of about 24 degrees. While this study did not include human subject testing, the information is still valuable for this specific scenario. That said, there is much more to understand to develop a comprehensive firefighting design (e.g., precision aerial retardant drops, reconnaissance, resupply and rescue operations, etc.).

To efficiently address the shortcomings of handling qualities for rotorcraft, VAERA intends to collaborate with its partners to solicit feedback from firefighting pilots on the major difficulties they face. These connections will also serve as an avenue for gathering information on potential flying quality degradations in these harsh environments. Flying and handling qualities are also relevant to UAS, which the VAERA project is also studying. Although drones may be remotely piloted, they will not have the same physical human interaction as piloted vehicles. The drones could therefore attain a higher amount of maneuverability than human-rated vehicles. In particular, this maneuverability is even more feasible for smaller vehicles that have smaller moments of inertia (assuming it has sufficient actuators to enable the more dramatic movements). However, these smaller moments of inertia make the smaller UAS more susceptible to the harsh winds, gusts, vortices, etc. of the environments they are intended to fly in. Additional challenges may also arise for the case when these smaller UAS vehicles are remotely piloted, since the pilot would have significantly reduced situational awareness compared to flying directly in the cockpit of a crewed vehicle. Thus, understanding, characterizing, and improving the flying qualities for these vehicles will have high priority during the development process. Once the critical mission scenarios have been decided, VAERA plans to expand upon existing NASA tools and processes for creating and assessing conceptual design vehicles.

**Small eVTOL UAS Technology**

Small eVTOL UAS may be beneficial in accomplishing tasks that are impractical or dangerous for crewed aircraft (see discussion in Current Wildfire Response section). In the context of this work, a small UAS is considered to have a gross weight under 1000 lb. In wildfire fighting, firefighters often travel on foot through wilderness, only transporting what they can carry. Small UAS would be useful for quick delivery of additional necessary supplies and would be more practical to keep on standby at the nearest road-accessible area than a crewed-class vehicle. For the purposes of the present discussion, a notional small UAS "supply drop mission" will be considered. A payload capacity of 100 lb and a range of 10 miles are defined for this notional mission.

Figure 3 reflects a survey of twenty-eight, sub-1000-lb commercial rotorcraft systems, including several fossil-fuel-powered aircraft, battery-powered aircraft, and one hybrid eVTOL. Generally, electric vehicles of this weight class are limited to lighter payloads and smaller ranges than gas/jet fuel vehicles due to available power. This trend may eventually be altered through improvements to battery technology, which would enable more capable eVTOLs. While performing the previously described mission with an electric vehicle is not beyond the state of the art from a payload/range standpoint, this survey suggests that there is currently a limited number of eVTOL platforms with the necessary payload/range capabilities. The majority of commercially available small UAS are designed to be flown under FAA Part 107, limiting their gross weight to 55 lb, and not meeting the 100-lb payload criteria [57]. UAS in the 55 to 1000-lb size class are less readily available and typically more specialized and expensive. Operation of a UAS greater than 55 lb also requires requesting an exemption to Part 107 in accordance with 14 CFR Part 11 [58] and the Congressional authority granted in Special Authority for Certain Unmanned Systems, 49 U.S.C. §44807 [59].

To reiterate, a wildfire produces an extremely adverse atmospheric environment. The gusty, turbulent aerodynamic conditions present significant challenges for VTOL design and operational performance. Unfortunately, these challenges are often overlooked in current design processes, including for many of the advertised vehicle capabilities captured in Figure 3, which are generally for standard atmospheric operating conditions. The work proposed in this paper would enable the analysis of aircraft in wildfire conditions to gain an understanding of the additional vehicle performance requirements imposed by the challenging conditions.

Aircraft flying in the wildfire environment should be designed and analyzed in those conditions to determine power requirements and trade-offs between gust rejection and speed/payload/range. Properly designing and analyzing a rotorcraft in wildfire conditions requires the quantification of these conditions via an accurate model of the flight environment (as described earlier) and capability to evaluate the additional rotorcraft performance and control requirements. The ability to accurately model the flight environment at the conceptual design stage may lead to improved, more capable wildfire aircraft designs at lower development costs.

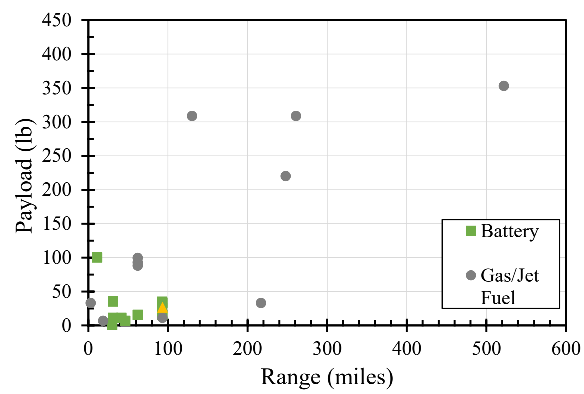


**Figure 3. Payload vs range for sub-1000-lb commercial UAS.**

**Subsystem Design**

Although different wildfire missions are still being identified, there are a few key subsystems of interest that could dramatically improve mission capabilities for wildfire scenarios. These subsystems include a lightweight and robust thermal cooling system, a reliable payload release mechanism/system, blades designed for the wildfire environment, and improved battery capabilities. There are many other subsystems that could be improved and employed on wildfire-fighting rotorcraft, but for brevity, only the listed subsystems will be discussed in this work. Improvement, and in some cases redesign, of these subsystems could have a major impact on the performance, flight dynamics, and mission capability of these vehicles.

*Thermal Cooling System*

In addition to the turbulent and gusty winds, another factor preventing rotorcraft from flying too close to the flames is the high temperature environment. There are a plethora of sensitive electrical components and sensors on various rotorcraft that cannot exceed temperatures higher than about 140°F (60 °C). For example, manufacturers recommend not to exceed 140 °F (60 °C) for both lithium-ion and lithium-polymer batteries. As discussed in the Wildfire Environment Modeling and Simulation section, the environmental temperature can get quite high, easily exceeding 120 °F (49 °C) with isolated packets of air exceeding 250 °F (121 °C) up to 100 feet above the fire [39]. Thus, the need for a thermal cooling system that is lightweight (to maximize allowable payload) and compact (to reduce surface area and volume) is crucial.

Thermal cooling systems implemented on smaller rotorcraft are not very common. The Imperial College of London and Empa have built a drone, the FireDrone, which has a maximum allowable temperature of 392 °F (200 °C) [60]. The primary purpose of the FireDrone is to be deployed in extreme environments to reduce the risk to human life. The FireDrone has a layer of PI aerogel, $CO_2$ gas to cool critical components, and a reflective outer layer of aluminum, to keep the drone cool. Although the drone has undergone flight tests at a firefighter training facility, there is limited published information on the details of these tests (i.e. temperature, duration in fire, number of flight tests), so it is assumed further testing is needed to prove its reliability and repeatability. Additionally, there was no indication that the flight tests were conducted in a turbulent environment. The work with the FireDrone is ongoing and although it is a promising step in the right direction, the vehicle has not yet been proven capable of flying in turbulent environments or of flying repeatedly in hot temperature environments.

Many helicopters in use today have a system for cooling their engines, but these systems usually rely on the ambient air. In extremely hot environments, the ambient air is too hot to cool down the engine, and an alternative system must be used to cool down the engine and the cabin, which houses other electrical equipment.

Thermal cooling systems for larger rotorcraft have an advantage over smaller rotorcraft because the ratio of the thermal cooling system weight to the overall weight of the vehicle is much smaller. Thermal cooling systems for this extreme environment are difficult to design for smaller vehicles due to very limited space. However, with larger vehicles, there is a larger volume of items that need to be cooled. There are few publications on thermal cooling systems for rotorcraft in environments hotter than 104 °F (40 °C). A thermal management system for a helicopter described in one study was based on an antifreeze liquid cooling loop and a vapor compression refrigeration loop which was able to maintain a temperature of 72-75 °F (22-24 °C) for ambient air up to 104 °F (40 °C). [61]. Another study showed how an integrated thermal management system with a heat pump air conditioning system, based on waste heat recovery from the lubricating oil system, was able to maintain a temperature of 77 °F (25 °C) again with ambient air up to 104 °F (40 °C) [62]. As previously stated, the wildfire environment can reach temperatures of 120 °F to 250 °F (49 °C to 121 °C). Thus, thermal cooling systems for both large and small aircraft remain an area of interest for further research.

*Payload Delivery Methods*

Another subsystem that could be improved for wildfire relief rotorcraft is the payload release mechanisms or systems. The notional wildfire mission described in the previous section involves payload delivery of equipment. There are several different methods on the market for releasing or lowering a payload to the ground. Analyzing each of the payload delivery methods listed below for this wildfire mission shows that none of them are ideal. The payload delivery methods and their associated problems are listed below.

1. Lowering the payload via a cable:
    - The rotorcraft needs to be hovering for an extended period of time, which depletes the battery.
    - Lowering the payload via a cable is difficult to do in a windy environment; the payload and vehicle can get blown around, and if there are trees nearby, the cable and/or payload could become compromised.
    - Cable and release mechanism adds extra weight.
    - Example of aircraft using this method of payload delivery: [63].

2. Dropping the payload with an attached parachute:
    - The wildfire environment is very gusty, which could blow the parachute/payload off course, into nearby trees, or into the fire.

- Issues with parachute deploying in a gusty environment.
- Examples of aircraft using this method of payload delivery: [64] [65].

3. Landing the vehicle and manually detaching the payload:
   - Landing the vehicle, restarting the rotors, and taking off again depletes the battery (the rotors would need to be stopped for the payload to be removed manually).
   - Personnel must be present to detach the payload.
   - Must have a reasonably flat surface to land on.
   - Must have an unobstructed flight path to the landing site.
   - Example of aircraft using this method of payload delivery: [66].

There are several companies that have commercially available drones and hardware that can be attached to drones to enable payload delivery via lowering the payload via a cable. There are a few references that explore developing control systems for drones carrying slung payloads via a cable [67] [68] [69]. Additionally, some new designs are emerging that incorporate an additional mechanism to help stabilize the payload being delivered by the cable [70] [71]. These new designs do not have published material on any testing or functional prototypes, so it is assumed that additional work needs to be done on these concepts. If these new designs are able to maintain enough control of the vehicle and payload to make a safe payload delivery in the turbulent wildfire environment with potential obstacles, the issue of depleting the battery still exists.

The benefit of the last method (manual detachment of the payload) is that a release mechanism is not required and thus overall weight and complexity are decreased. Often, if firefighters are present, they can make a landing circle for a helicopter. However, if the mission is to deliver a payload prior to personnel being present, the vehicle will have to wait for personnel to arrive and detach the payload, and finding a place to land while waiting may be difficult. Additional information on the challenges of small UAS and delivery drones can be found in Chopra's comprehensive Nikolsky Honorary Lecture [72].

Existing options for payload delivery are not designed with wildfire missions in mind. More design work on the payload release methods, mechanisms, and systems for wildfire missions is required.

*Wildfire Rotor Blades*

Depending on the desired flight proximity to the wildfire, the increased air temperature and its associated reduction in lift generation can significantly reduce the capability of any aircraft. This is because, when the temperature of the ambient air is hot, air molecules move further apart, creating less dense air, making it more difficult for the helicopter to produce lift [73]. Thus, designing rotors to operate best at the high temperature, low density conditions near fires could expand the operational limits of the wildfire aircraft.

Previous work has been done to optimize rotors for different environments. For example, Koning et al. has developed the Evolutionary Algorithm for Iterative Studies of Aeromechanics (ELISA) tool for optimization of rotor blades in support of the Rotorcraft Optimization for the Advancement of Mars eXploration (ROAMX) project [74]. The airfoil coefficient of lift over the coefficient of drag ($c_l/c_d$) of the ROAMX rotor airfoil at 75% radius is 28% higher (at equal lift) compared to that of the Ingenuity airfoil [74]. Using the ROAMX-1301 parameterization, a $c_l/c_d$ increase of 42% compared to the Ingenuity airfoil was obtained [75]. While it is unlikely that optimizing the rotor design for a wildfire environment would produce a performance increase of the same magnitude as optimizing for Mars, the tool/process was developed with extreme environments in mind and could be applicable for wildfire blade optimization.

Additional studies showed other methods for designing optimized rotors for small rotors in a quadrotor configuration [76] and for industrial helicopter rotor blades [77]. The first study [76] uses a hybrid optimization scheme coupled with an aerodynamic performance code and presented two optimized rotor cases: high altitude and long endurance flight, and best thrust to power ratio at a required thrust in climb. The second study mentioned [77] uses an optimization loop that couples the Dakota optimization library, a comprehensive rotor code, and a CFD solver. The example presented in this study is the optimization of the rectangular 7A wind tunnel blade. These studies show that additional rotor optimization methods exist, although few of them have been used for extreme environments similar to the turbulent wildfire environment.

*Battery Systems*

Battery capability is one of the lead limiting factors on the payload versus range trends. Many companies have been working toward developing more powerful and lightweight batteries. Two different studies look at the possibility of using nanoelectrodes and silicon-nanowire for lithium-ion batteries [78] [79]. NASA has also been working to develop Solid-state Architecture Batteries for Enhanced Rechargeability and Safety, SABERS [80]. The SABERS concept proposes a battery that meets the key performance criteria through development of a solid-state architecture battery utilizing high-capacity sulfurselenium cathode and lithium metal anode [80]. As shown in the earlier Small eVTOL UAS Technology section, eVTOL payload/range capabilities are generally limited compared to gas powered rotorcraft. Implementing future technology that focuses on improving battery efficiency is important if these next generation eVTOLs will be fully electric. There are multiple entities with significant expertise and experience investigating this issue, so battery system improvement will not be further pursued by this project as a research topic at this time. This paper seeks only to acknowledge that it is a technology gap.

## PROPOSED RESEARCH

While the topics discussed above do not comprehensively cover all technology gaps related to rotorcraft operating in wildfire conditions, the technology gaps presented are significant enough to justify discussion of actions that could be completed with existing or near-term innovation. The goal of this proposed research is to improve vehicle technologies and capabilities for an array of wildfire-fighting rotorcraft. A by-product of this proposed research would be conceptual and preliminary vehicle designs, improved handling and flying quality models, improved turbulence models, and improved subsystem designs for a variety of wildfire missions. This section explains how the proposed research goals can be accomplished through discussing the methods of addressing each of the identified technology gaps for rotorcraft in the wildfire environment. The identified technology gaps are as follows:

- Poor performance and handling/flying qualities
- Poor or nonexistent categorization of handling qualities
- Inadequate flight dynamics turbulence modeling approaches
- Inadequate subsystems for wildfire missions

The formal design process starts with a conceptual design, then advances to a preliminary design, and finally comes to a detailed design. The designs that would be generated through the proposed research described in this section would include both conceptual and preliminary designs. These designs could then be used in future work to support detailed design, analysis, and testing, but these stages are not currently included in the scope of this proposed research.

Flight dynamics, and by extension flying/handling qualities, are essential to the design process, especially for vehicles in a size range that is susceptible to gusts of the magnitude commonly produced by wildfires. Uncharacterized flying qualities can significantly bound potential performance. Existing rotorcraft design and analysis tools can be used in the vehicle design process with flight dynamics as a part of the design loop. However, before these tools are applied for wildfire situations, the models/guidelines that feed into the tools must be sufficiently updated.

A flow chart of the flight dynamics design loop is given in Figure 4. After sufficient background research has been completed and technology gaps identified, the next step is to define relevant mission profiles (see the Small eVTOL UAS Technology section for a simplified example mission profile). Many of the mission profiles will include changes in weight/inertias throughout the mission profile, from tailoring both the overall vehicle geometry and different subsystems to the specific mission profile, which would impact flight dynamics. Once the missions are defined, they can serve as a starting point for sizing the vehicle using an aircraft sizing tool like NDARC, NASA Design and Analysis of Rotorcraft, Validation and Demonstration [81]. NDARC is a rotorcraft sizing code based on component level parametric models of weight and performance derived from existing aircraft. Additionally, NDARC can be used to sweep a series of conditions, such as changes in ambient conditions (from different strengths of wildfires), payload weights, and

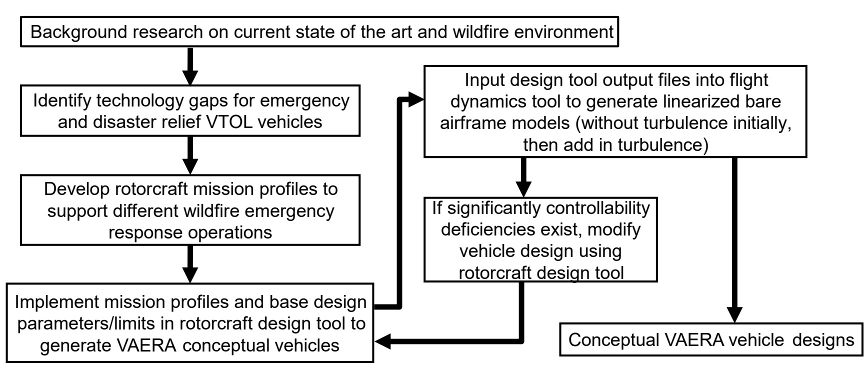


**Figure 4. Vehicle design flow including controllability considerations.**

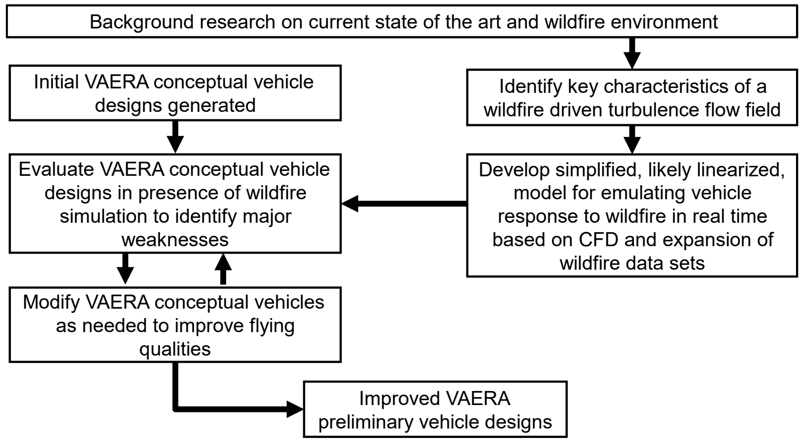


**Figure 5. Vehicle design iteration using simulated wildfire environment for improved flying qualities.**

other vehicle parameters like weight of thermal cooling systems, rotor size, and engine/battery capability. These trade-off studies would help to determine which design changes would be most likely to improve the performance, identify any design constraints, and could also produce conceptual design point selections for further exploration and study.

Most current conceptual design tools do not include dedicated flight dynamics modules. However, flight dynamics characteristics and impacts can be evaluated using separate tools and then iteratively fed back into the sizing tool as needed. For example, though not publicly released yet, FlightCODE, developed following the guidelines laid out by SIMPLI-FLYD [82], is a complementary tool that reads NDARC output files as input and, among other functionalities, then generates linearized bare-airframe models. If the linearized bare-airframe reveals significant controllability deficiencies, the designer can alter the vehicle design early in the design process, rather than investing significant development resources to discover this flaw at a later time, saving time and resources. Instability, control power available, control effort to stabilize the aircraft, and control augmentation would be considered within the controllability assessment. Power margins could be determined from the NDARC output; however, a more detailed design and analysis of the controller would need to be performed to assess other control factors before integrating the vehicle into a more complex simulation.

Once a conceptual vehicle design is generated, the next step is to evaluate how the vehicle behaves in a low-fidelity flight dynamics simulation, see Figure 5. Such an analysis can be completed through the utilization of numerous mid/low fidelity rotorcraft-based design softwares, including but not limited to FlightCODE, FLIGHTLAB, and HELIUM [83]. The simulation allows many shortcomings of the design to be addressed before vehicle hardware investment, and better informs safety. In addition to the checks of the linear bare airframe in Figure 4, Figure 5 includes a more robust modeling approach for the turbulence specific to wildfires. Utilizing a more generic turbulence model in the design process described in Figure 4, can possibly improve convergence by providing starting conditions for the more extreme wildfire turbulence model, instead of trying to get the model to converge independently. If a stable, controllable vehicle design cannot be identified, then the vehicle design must be modified as outlined in the procedure in Figure 4. Subjecting the vehicle to the initial flight dynamics software described in Figure 4, prepares the vehicle design for the more intensive simulations shown in Figure 5. Existing wildfire data must be extrapolated to broader generalized models able to run in real-time. This process would likely involve comparing high- and mid-fidelity CFD models to produce a representative set of equations. These models would not capture every extreme condition the vehicles might encounter but should be sufficient to inform design decisions before advancing to future stages involving prototype development and flight testing. Like the process before, the conceptual vehicle designs would be subjected to the wildfire simulations to identify weaknesses, and the vehicle designs would be modified in an iterative loop until sufficient handling/flying qualities are met. The final product of this process is preliminary vehicle designs for specific wildfire missions that have improved flight dynamics in the wildfire environment.

The process above would likely be sufficient for smaller, autonomous vehicles. If the vehicles were larger and piloted or sensitive to remote control inputs from pilots, additional analysis may be required to account for handling qualities, including the effect of the pilot in-the-loop, rather than just the behavior of the vehicle. This could involve doing a more formal handling qualities test

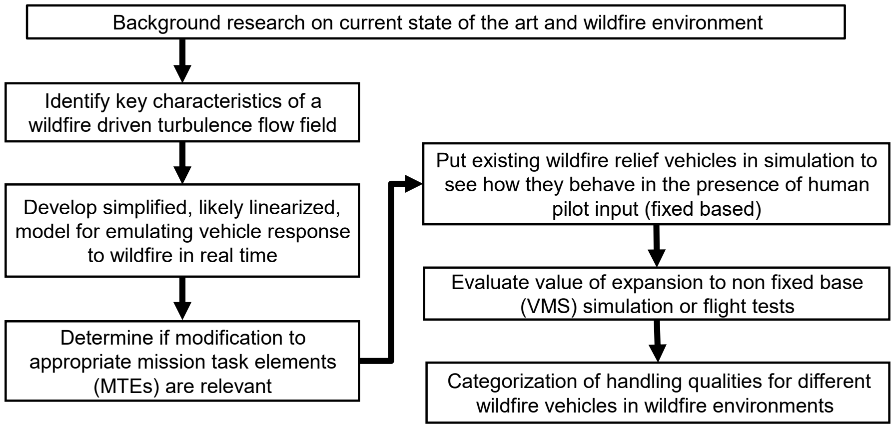


**Figure 6. Sequence of events for categorization and identifying handling qualities in the wildfire environment.**

campaign utilizing facilities such as the Vertical Motion Simulator (VMS) at NASA Ames or even flight testing once the models had sufficiently matured. For either fixed-based or motion testing (VMS or flight), evaluating the relevance of mission task elements, which are historically based primarily on military task operations, to the wildfire environment is essential. This process is outlined in Figure 6. One of the final outcomes of a handling qualities test campaign would be the categorization and identification of handling qualities for different wildfire vehicles in the wildfire environment.

The last of the identified technology gaps that will be addressed in this paper is the improvement of specific subsystems for wildfire rotorcraft. As discussed in the previous section, the subsystems needing improvement include (but are not limited to): the thermal cooling system, the payload release mechanism/system, the battery system, and rotor blade design for the wildfire environment. The weight and geometry of these subsystems will need to be included in the aircraft sizing tool. Additionally, the payload release mechanism and the rotor blade design will greatly influence the flight dynamics and performance of the vehicle. Thus, the research on the various subsystems will inform the conceptual and preliminary vehicle designs.

For addressing improvement of the thermal cooling system, two systems of cooling on board the aircraft are suggested: active cooling and passive cooling. The active cooling system would actively work to decrease the internal temperature of the aircraft. Example approaches include using $CO_2$ gas, similar to the FireDrone, or could be as simple as strategically placing ice packs inside the vehicle fuselage prior to short flights (depending on resource availability). As stated earlier, typical engine cooling systems that use the ambient air to cool down the inside of the aircraft would not be feasible in the hot wildfire environment. Some of the newer cooling methods mentioned in the previous section could be considered, but those have not been proven to work in environments hotter than 104 °F (40 °C). Tradeoff studies for different approaches would be necessary to determine which method would be the most efficient for each mission.

The passive cooling system involves isolating and protecting the aircraft from the hot external environment rather than actively trying to cool it down. Using a thermal insulating and potentially fireproof (depending on the mission) layer of material on the surface of the vehicle is one approach. An extreme example of this would be the thermal insulating tiles or the heat shield used on vehicles re-entering Earth's atmosphere. Other approaches could use materials of high emissivity on the top of the vehicle, with a low absorptivity (light colored or reflective) material on the underside of the vehicle. This method may be useful for reflecting the heat underneath the vehicle and dissipating the heat on the top of the vehicle, for fly over missions. However, this method may not be suitable for missions requiring the vehicle to go closer to the fire. Different materials should be explored to determine their compatibility with each vehicle and each mission. Next, the materials' feasibility of implementation and manufacturing should be considered. Certain materials may not be conducive to aerodynamic geometries or may be quite heavy or expensive, thus a cost-benefit analysis may need to be performed to determine how a less aerodynamic and/or heavier fuselage could affect the performance and flight dynamics of the vehicle. Implementing the thermal cooling system while maintaining optimal flight dynamics and performance will likely be an iterative process.

The design process for the payload release mechanism/system would be similar to that of the thermal cooling system. First, each of the different payload release methods would be assessed to determine which methods are the most advantageous for each wildfire mission. This would likely involve devising new payload release methods since the existing methods described in the previous section have several downsides. After a few of the preferred methods are selected, the subsystem would be designed for and implemented into the mission specific conceptual vehicle designs. Different payload release systems (and even different design iterations of the same system) would have various effects on the performance and flight dynamics of the vehicle. The performance and flight dynamics would need to be reassessed several times during the design process to ensure that the payload release system does not impede the vehicle's ability to complete the mission. This design process would likely go through many iterations before converging on the most favorable design (lightweight, compact, minimal effect on flight dynamics and performance).

Existing technology, design processes, and tools could likely be utilized for the thermal cooling system and the payload release mechanism/system, as these systems are common in other fields. The technological obstacle involves the task of modifying existing or designing new thermal cooling and payload release systems to meet the specific demands of the wildfire environment while ensuring smooth integration with specific vehicle designs. This undertaking could lead to the development of breakthrough designs with potential practical uses beyond the scope of wildfire missions.

The next subsystem that would drastically improve performance and capability of rotorcraft in general (not just wildfire rotorcraft) is advanced battery systems. As said before, the process for improving battery systems is not addressed in this paper, but it is important to acknowledge that battery performance is a significant technology gap that limits eVTOL.

The last technology gap addressed is designing blades specifically for the wildfire environment, leading to increased performance of wildfire rotorcraft. Comparing and analyzing the performance of different airfoil geometries for standard and extreme operating conditions is the first step. The airfoils that yield the best performance for turbulent flow, temperature fluctuations, air density changes (from heat and altitude), viscosity, and other wildfire environment characteristics, would be selected. The next step would involve sweeping different blade characteristics in a comprehensive analysis software (e.g. CAMRAD II) to analyze rotor performance and to identify preferable rotor geometry for standard and extreme operating conditions. This process has been used by the Aeromechanics Branch at NASA Ames for developing small rotor blades for multiple 7- by 10-Foot Wind Tunnel tests. This process is not a full optimization of the rotor blades. If after the initial rotor design process, a full optimization of the rotor blades is desired, a tool such as ELISA [74] could be used. The effect of the improved airfoil geometry on flight dynamics could be assessed using a tool such as FLIGHTLAB.

## SUMMARY

Being a wildland firefighter is a complex and hazardous undertaking that demands highly skilled personnel and specialized equipment. Still, every fire season, brave men and women put their lives at risk to protect our forests and homes. Reducing their exposure to danger and hazards is of the utmost importance and must be prioritized. This paper identifies some of the technology gaps that are currently limiting rotorcraft in wildfire relief efforts and proposes high level approaches and methodologies to address the issues.

Technology Gap 1: poor performance and handling/flying qualities in the wildfire environment. The wildfire environment has extreme temperature fluctuations that cause turbulent and dangerous wind gusts for all aircraft. Rotorcraft have degraded handling and flying qualities in this turbulent environment. If rotorcraft were designed and flight dynamics analysis were performed specifically for the wildfire environment, the rotorcraft may not only have increased capabilities but may also be able to perform missions once thought to be impossible. Incorporating flight dynamics into the design cycle would enable the vehicle design to be modified to increase handling and flying qualities for specific wildfire missions earlier in the process, saving time and resources.

Technology Gap 2: inadequate or nonexistent categorization of handling qualities in the wildfire environment. Understanding how different wildfire factors interact and the level of compensatory effort a pilot must exercise in order to operate a vehicle in different environments is crucial to flight safety. Currently, there exists a gap in knowledge on the handling qualities for certain wildfire environments and scenarios. Human pilot testing with existing and conceptual wildfire rotorcraft vehicles in fixed- and potentially motion-based simulations would allow more robust categorization of handling qualities for different wildfire rotorcraft in various wildfire environments, informing flight safety.

Technology Gap 3: unvalidated flight dynamics turbulence modeling approaches. While there are simulations that model the wildfire environment, simulations that can be coupled with flight dynamics models in real-time are needed. Exploring the trade space between modeling the complexities of a wildfire environment and running a real-time model, and then incorporating a mid-fidelity model into the design loop would allow the conceptual designs to be subjected to more realistic wildfire flow characteristics, yielding improved preliminary vehicle designs.

Technology Gap 4: subsystems need to be improved for wildfire missions. These subsystems include but are not limited to: a thermal cooling system, payload release mechanism/system, battery systems, and wildfire rotor blades. Batteries limit eVTOL aircraft performance, and wildfire rotorcraft are no exception. The paper acknowledges this technology gap but does not address battery development as a rotorcraft-specific challenge. The thermal cooling system for a rotorcraft flying close to the wildfire would need to be lightweight and incorporate both internal active cooling and passive thermal insulation on the surface of the vehicle. The payload release mechanism/system needs to be designed to work in a turbulent environment with several potential obstacles in its path. Finally, it is possible that designing rotor blades specifically for the wildfire environment could yield an increase in vehicle performance.

While a substantial amount of work is required to improve rotorcraft for wildfire missions, there has been a dramatic increase in interest in this area over the last few years. Government, industry, and academia will all play a role in developing the new generation of wildfire rotorcraft that will address the challenges discussed here and serve in this vital life-saving capacity.

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